Jet Propulsion Laboratory
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Attribution of Ozone and Methane Radiative Forcing in the Last Decade:

Impact on cumulative emissions and the Global Stocktake

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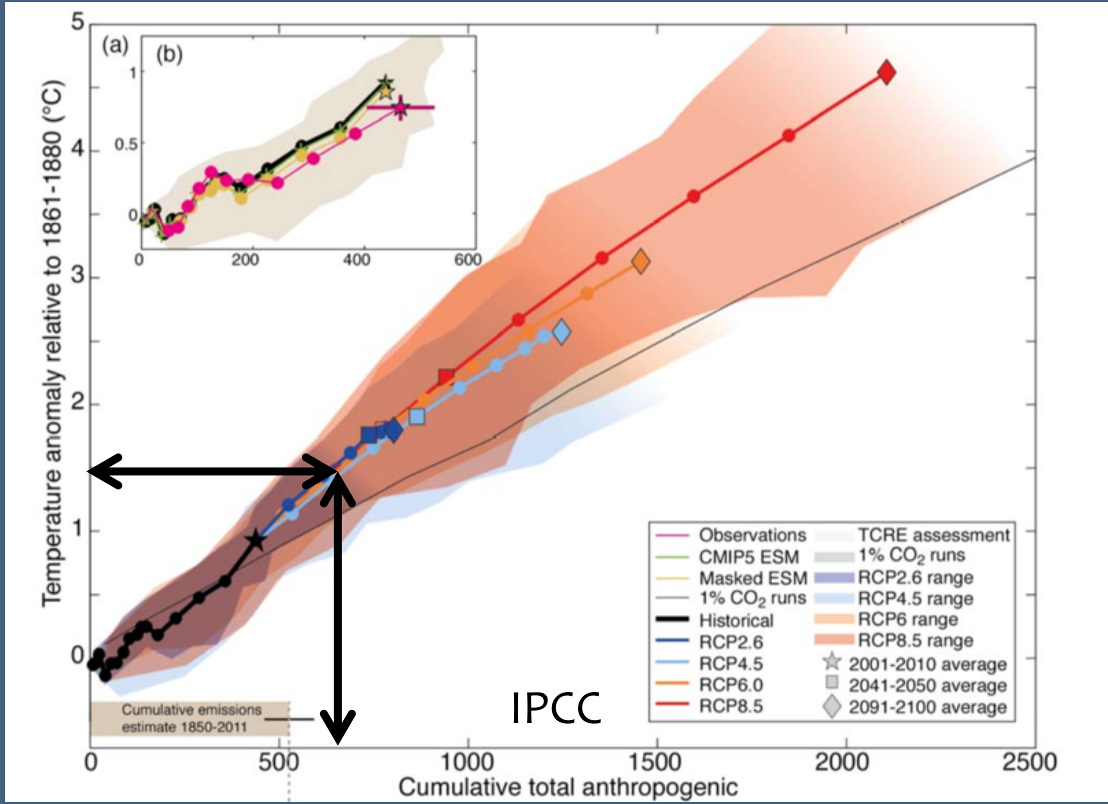
How much more greenhouse gas gases can we emit?

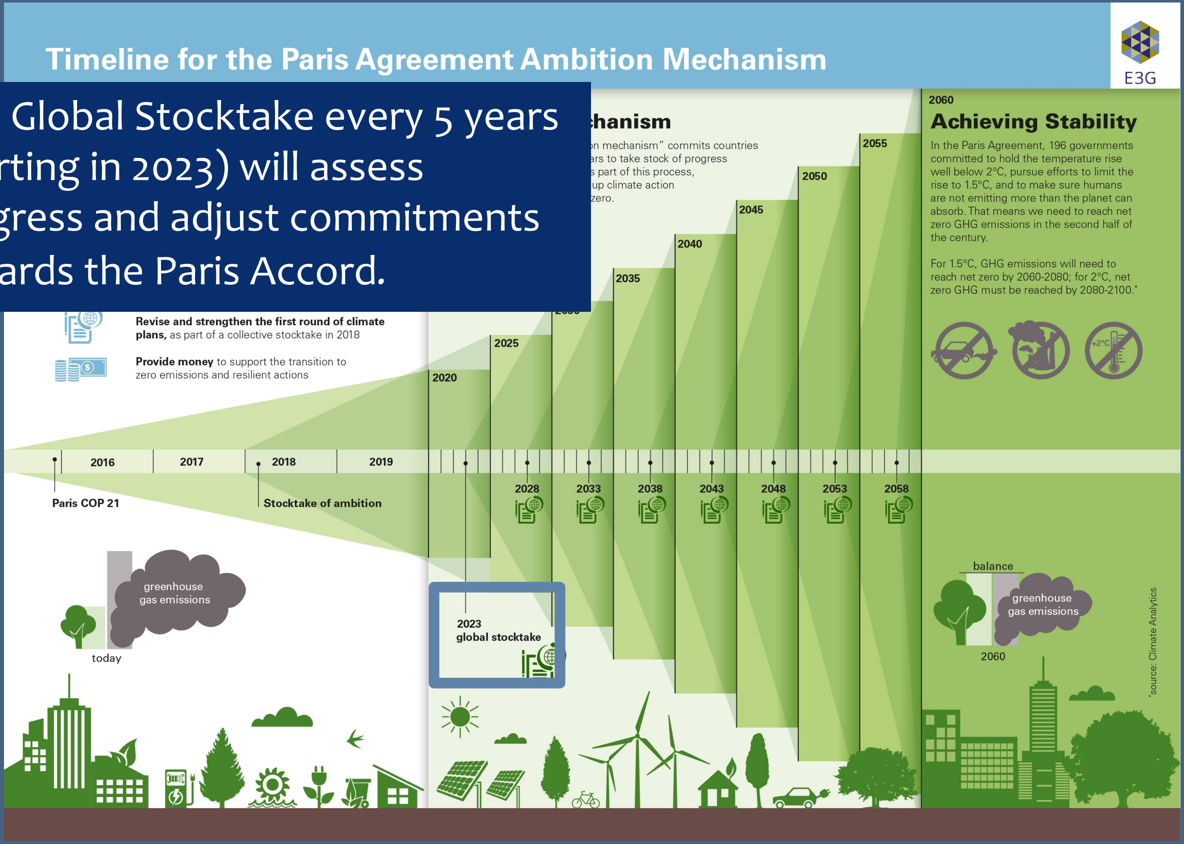
The Consumable Future: GHG budget

Temperature response is *roughly* proportional to cumulative carbon emissions (Matthews et al, 2009)



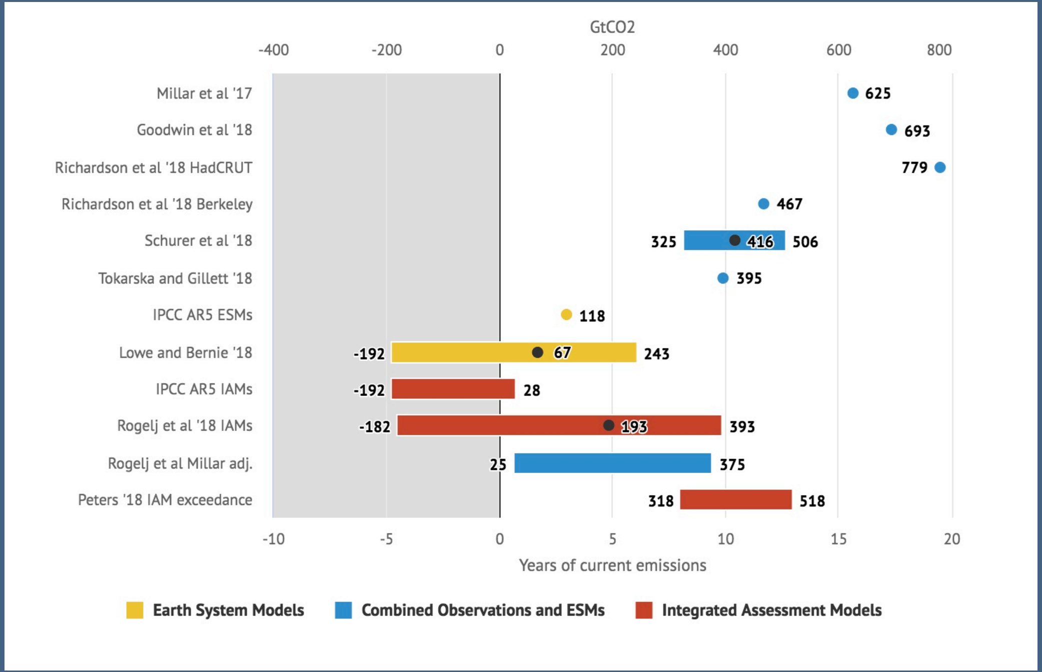
The Global Stocktake

The Global Stocktake every 5 years (starting in 2023) will assess progress and adjust commitments towards the Paris Accord.



Accounting confusion

Remaining carbon budgets in gigatonnes CO2 (GtCO2) from various studies that limit warming to a 66% chance of staying below 1.5C

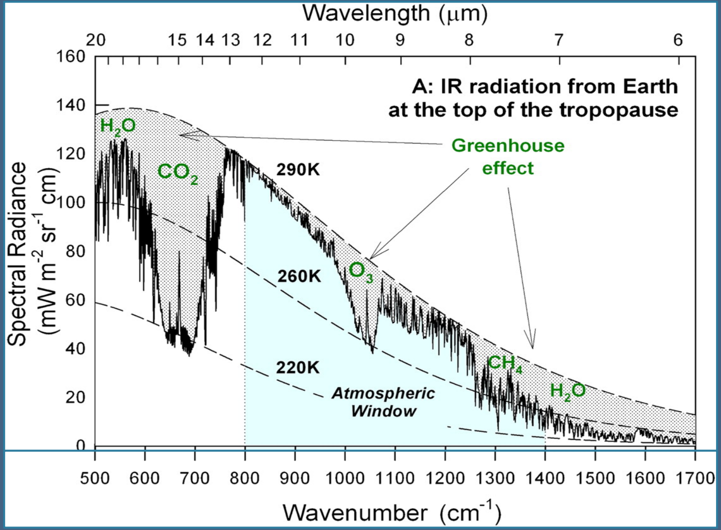


Z. Hausfather, Carbon Brief

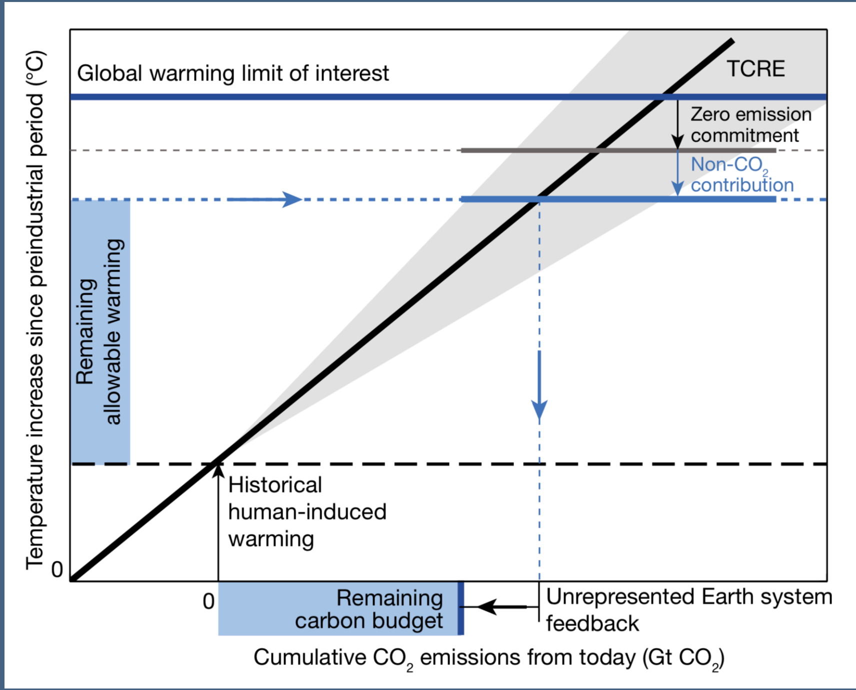
The uncertainties in allowable emissions is driven by 1) the relationship between concentrations and temperature and 2) the relationship between emissions and concentrations

https://www.carbonbrief.org/analysis-how-much-carbon-budget-is-left-to-limit-global-warming-to-1-5c

Radiative forcing from Climate Pollutants: Every Watt matters



Wallington T J et al. PNAS 2010;107:E178-E179



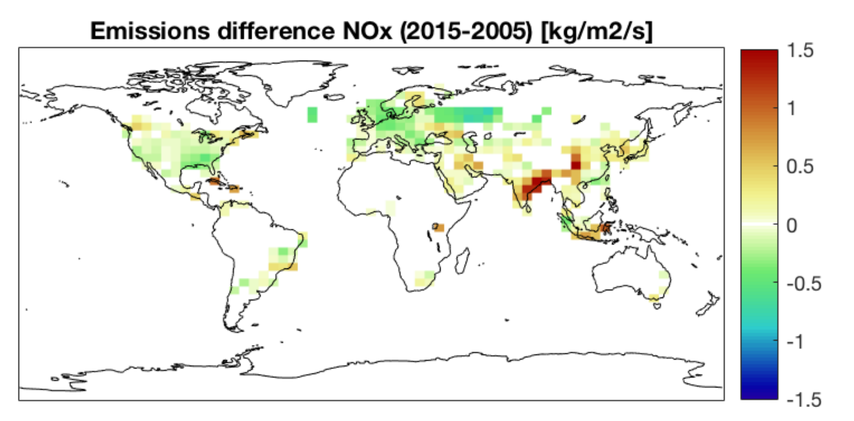
Rogelj et al, 2019

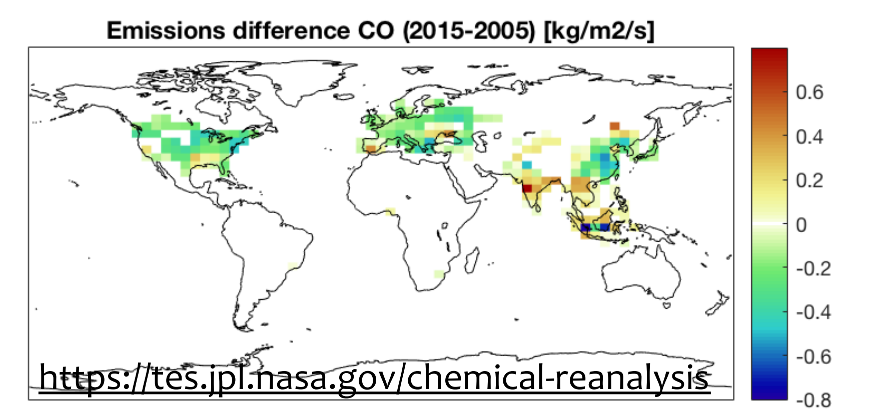
Carbon dioxide, methane, and ozone are the three most important greenhouse gases resulting from anthropogenic activities.

These gases are coupled through common sources and coupled within the Earth System.

Short-lived climate pollutants (non-CO2 contributors) impact the allowable emissions.

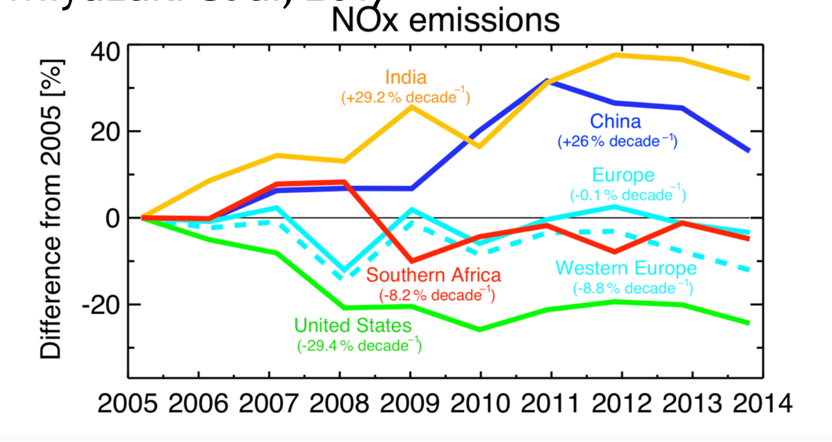
The Changing Landscape of Emissions





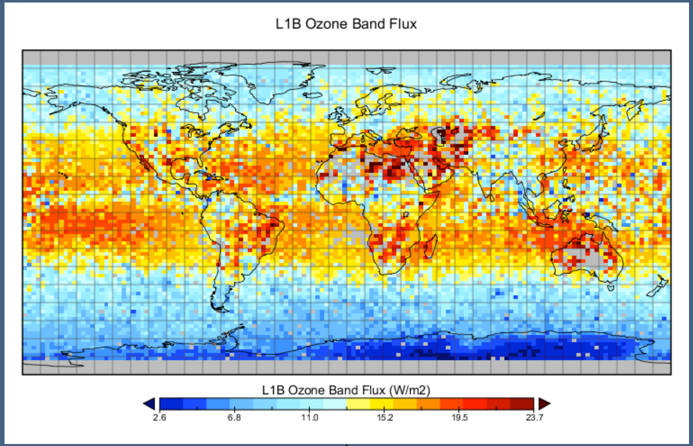
EOS "top-down" satellite observations (e.g., OMI NO2, MOPITT CO) have borne witness to a dramatic change in the landscape of emissions…
at stocktake timescales.

Miyazaki et al, 2017



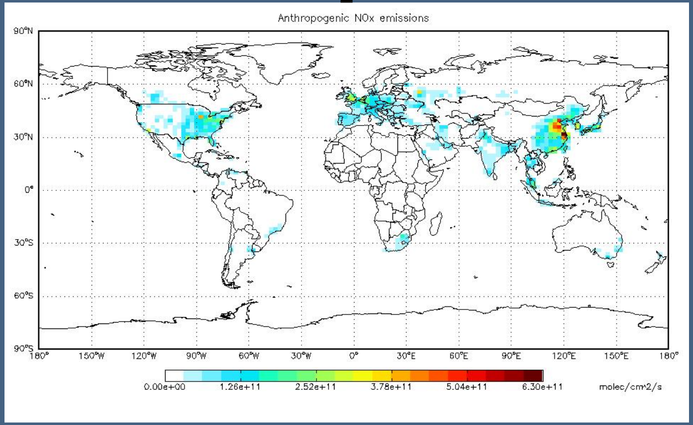
What is the impact of a NOx emission at one location on mean O3 OLR?

J=Mean



$$\mathcal{J} = \frac{1}{N} \sum_{i \in \mathrm{TES}} F_i$$

δJ(NOx)



$$\lambda = \nabla_{\mathbf{E}} \mathcal{J}$$

Connecting TOA to emissions

Sensitivity of TOA at one location with respect to precursor emissions ***E***=$[E_1, E_2, \ldots, E_N]$

Use chain-rule to link TES Instantaneous Radiative Kernels to emissions through GEOS-Chem adjoint

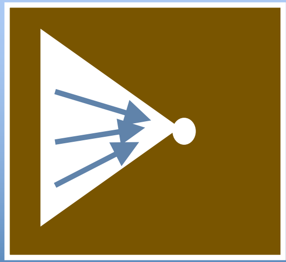
Bowman and Henze, 2012

$$\lambda^i = \frac{\partial F_i}{\partial \mathbf{E}}$$

$$\lambda^i = \left(\frac{\partial \mathbf{c}_i}{\partial \mathbf{E}}\right)^T \frac{\partial F_i}{\partial \mathbf{c}_i}$$

Model adjoint TES IRK

$$\frac{\partial \mathbf{c}^i}{\partial \mathbf{E}} = \frac{\partial \mathbf{M}_{i-1}}{\partial \mathbf{c}_{i-1}} \cdots \frac{\partial \mathbf{M}_0}{\partial \mathbf{E}}$$

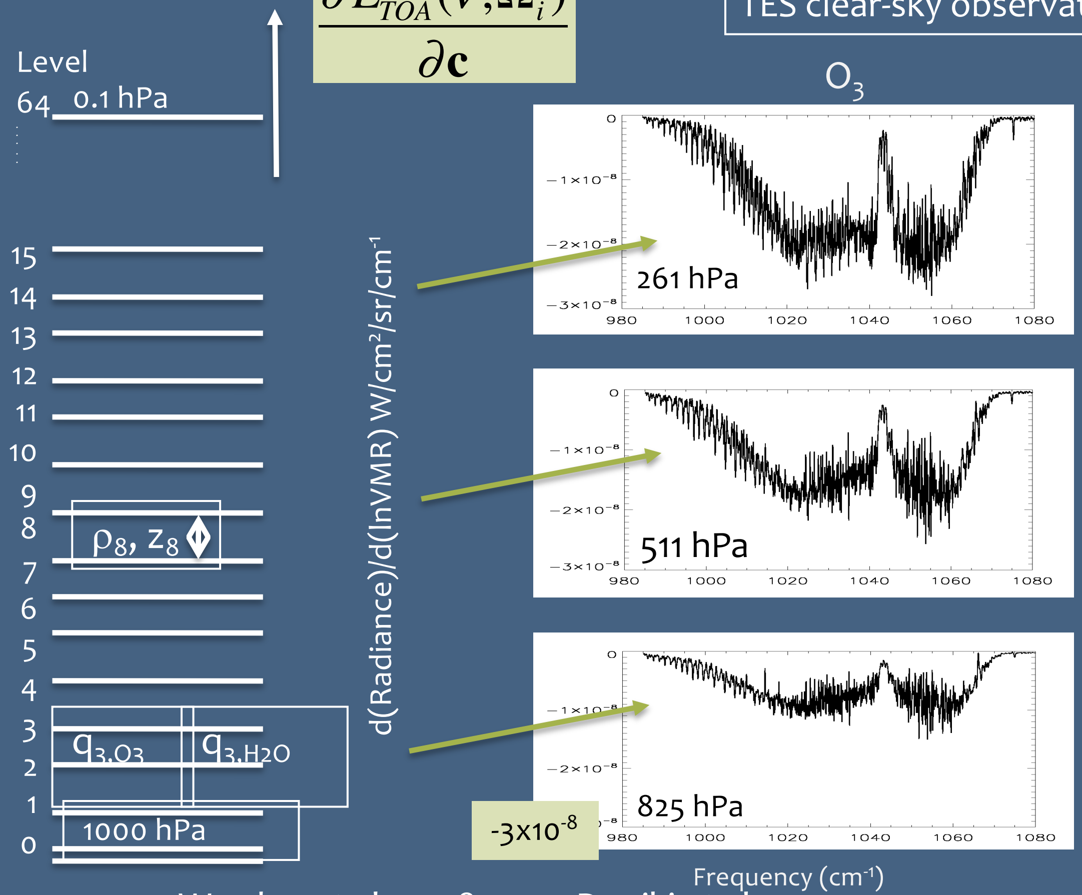


Adjoint accounts for both transport and chemical transformation

TES Instantaneous Radiative Kernels (IRK)

$$\frac{\partial L_{TOA}(\nu,\Omega_i)}{\partial \mathbf{c}}$$

TES clear-sky observation at 41°S, 150°W



$$\frac{\partial L_{TOA}(\nu,\Omega_i)}{\partial \mathbf{c}}$$

↓

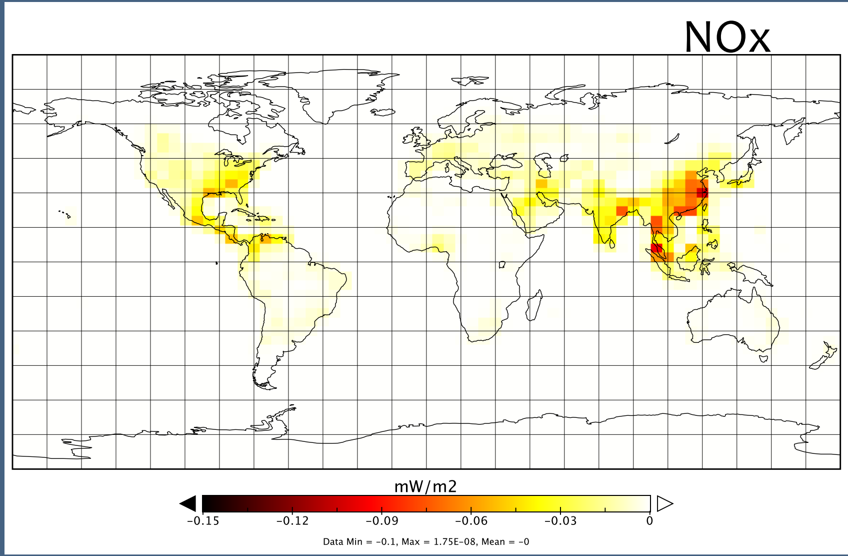
Integrate over solid angle and frequency

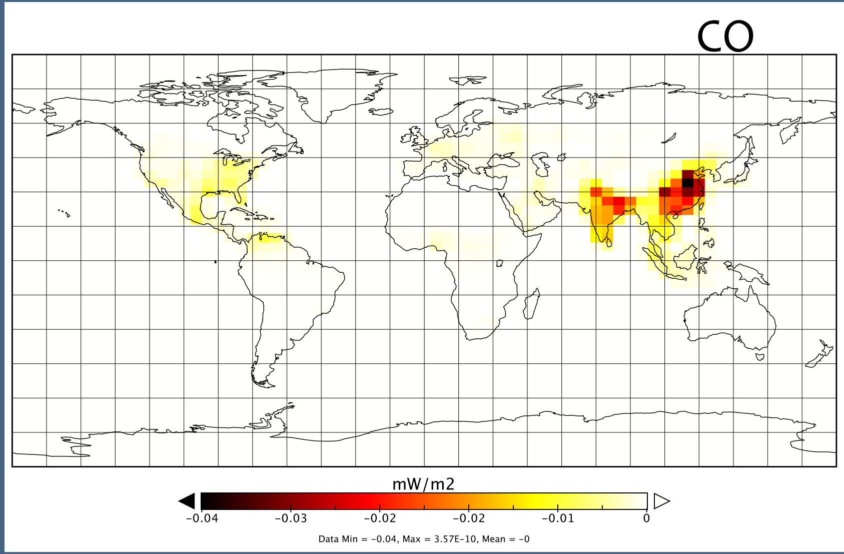
↓

$$\frac{\partial F_{TOA}}{\partial \mathbf{c}}$$

Worden et al, 2008, 2011, Doniki et al, 2015

Sensitivity of O3 Radiative Forcing to NOx and CO emissions for July, 2006





The sensitivity of O3 RF to NOx and CO emissions is dominated by China with fluxes exceeding 100 $\mu W/m^2$ /%E.

Indonesia has comparable sensitivity even though it has an order of magnitude less emissions (Bowman and Henze, 2012)

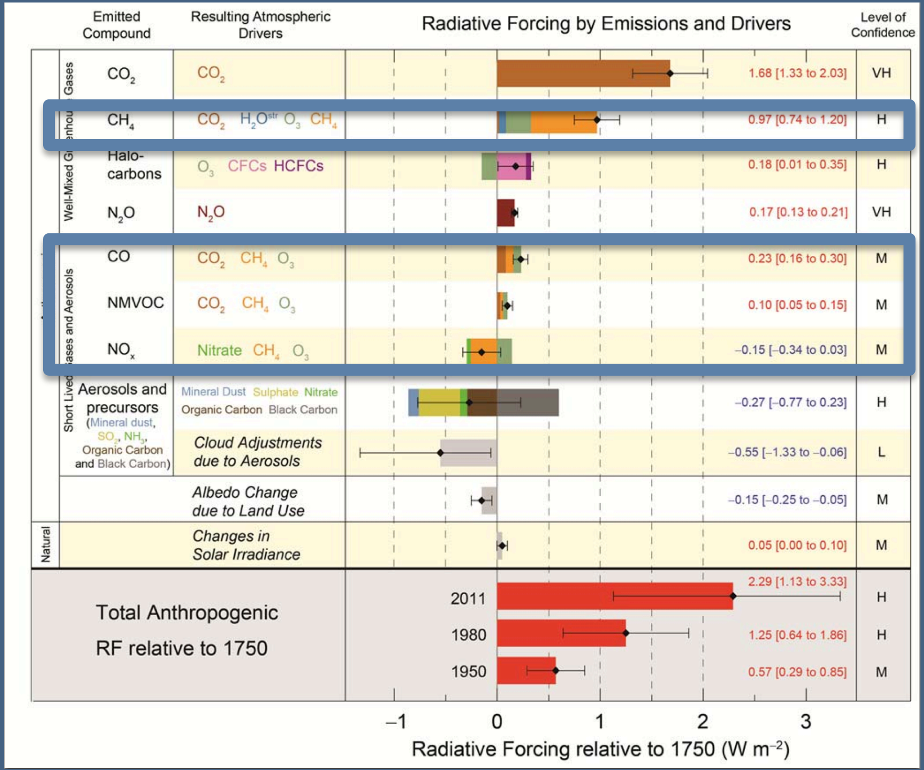
Tropical and subtropical regions dominate sensitivity because O3 is more efficient as a GHG.

Methane Radiative Forcing from NOx and CO

Historic Methane RF ~1 W/m²

Net CH4 is the balance of emission and chemical prod/loss

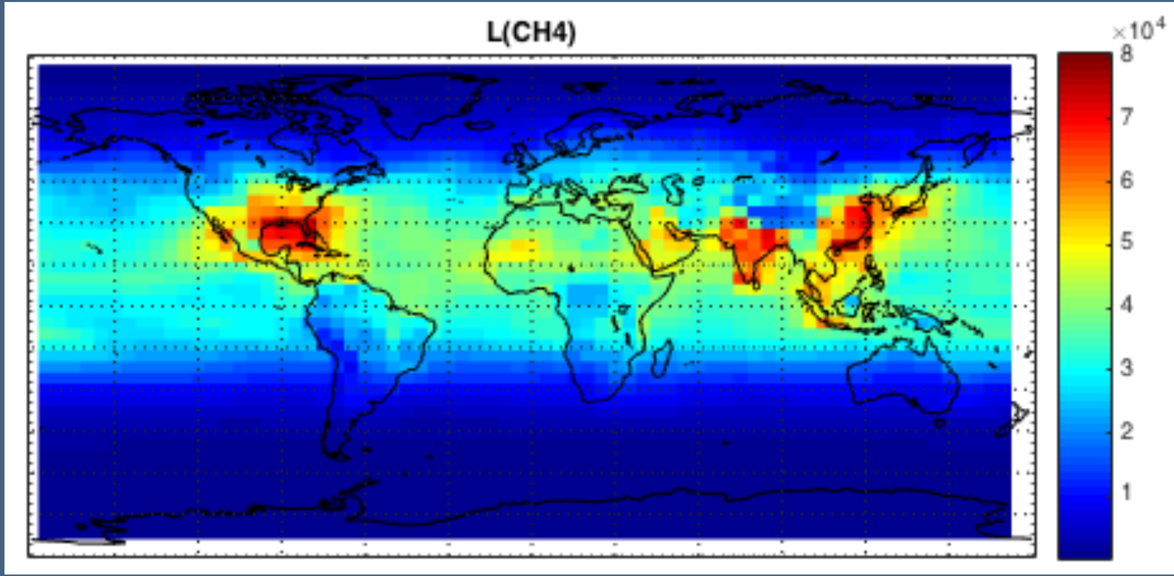
$CH4_{net} = CH4_{emiss} - CH4_{chem}$



Methane emissions:~640 (342 Anth+300 natural)
Methane chemistry: ~638 Tg

Ozone precursor emissions affect methane radiative forcing by changing its lifetime though control of OH.

Adjoint analysis of CH4 radiative forcing



Total chemical loss of methane is a function of the global distribution of OH

Sensitivity of methane loss to precursor emissions can be calculated with the adjoint

From methane lifetime change, radiative forcing can be calculated from simplified RT (M Etminan et al, GRL, 2016)

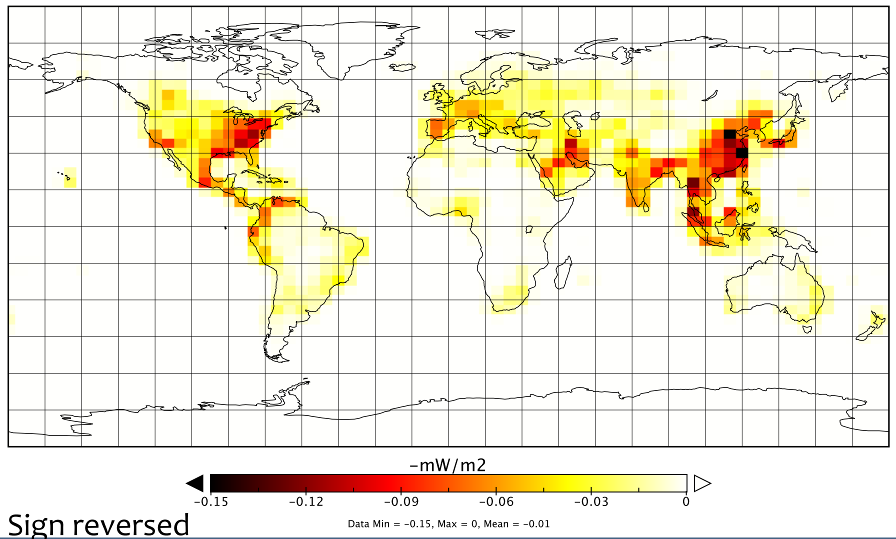
$$L(CH_4) = \sum_{i \in D} \kappa_i [OH]_i [CH_4]_i$$

$$\nabla_{\mathbf{E}} L(CH_4)$$

$$L(CH_4) \rightarrow \Delta CH_4 \rightarrow \Delta RF$$

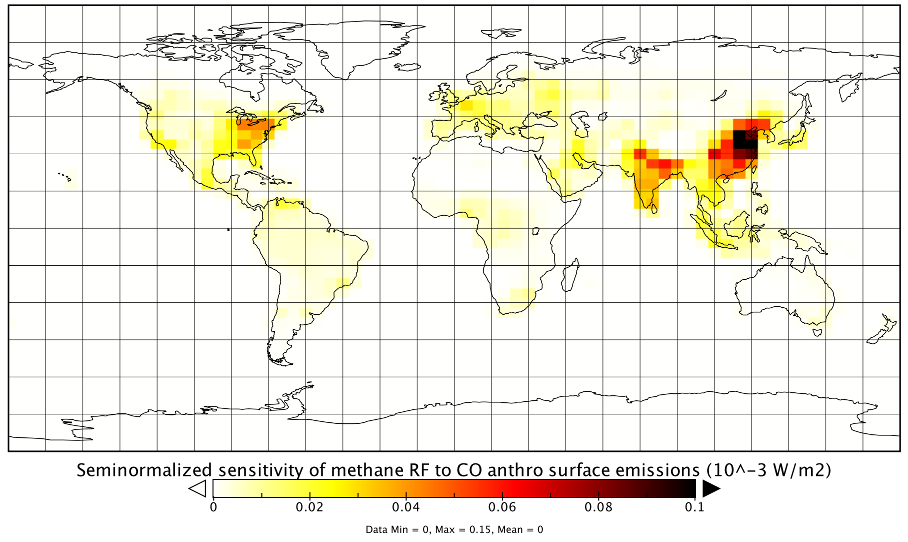
Sensitivity of CH4 RF to NOx emissions for July, 2006

NOx



Sign reversed

CO



The spatial pattern of sensitivity of CH_4 RF to NOx and CO emissions is similar to O_3 RF with peak magnitudes ~ 150 $\mu W/m^2/\%E$.

NOx and CO emissions have *opposite* effects on CH_4

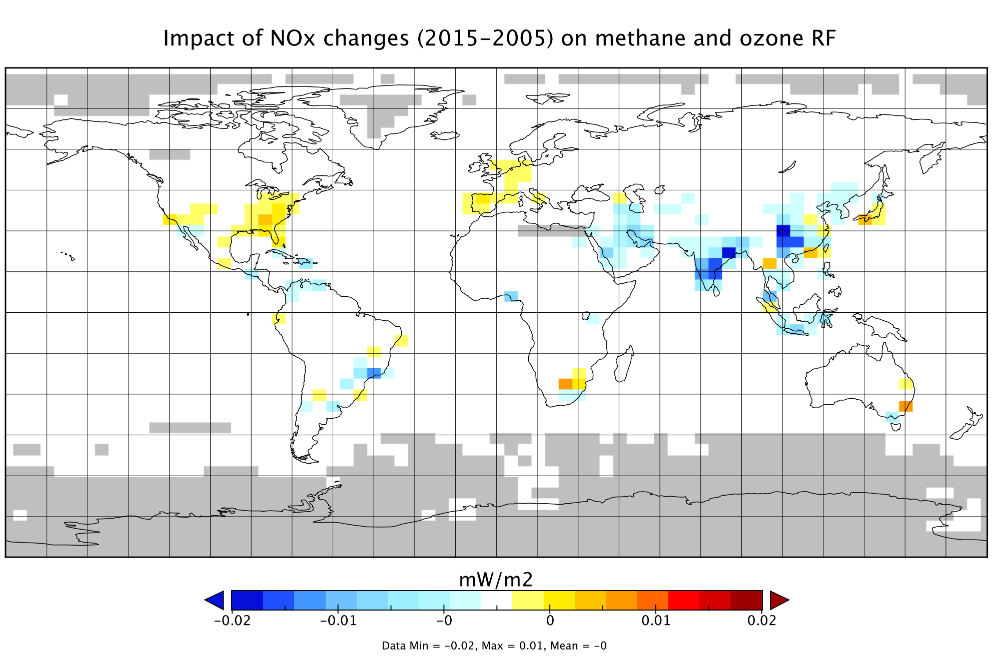
Contribution from India and the Middle East are much more prominent (Kuai et al, 2017).

Impact of decadal NOx emissions on O3 and CH4 Radiative Forcing

$$\delta RF_{CH_4,O_3} = (\nabla_{E_{NO_x}} RF)\delta E_{NO_x} + (\nabla_{E_{CO}} RF)\delta E_{CO}$$

Changes in decadal RF is driven by decreases in southern China and southeastern India as a consequence of net increase in NOx emissions (max ~0.02 mW/m²)

These were offset by modest in increases in decadal RF from NOx emissions reductions in North America and Europe.

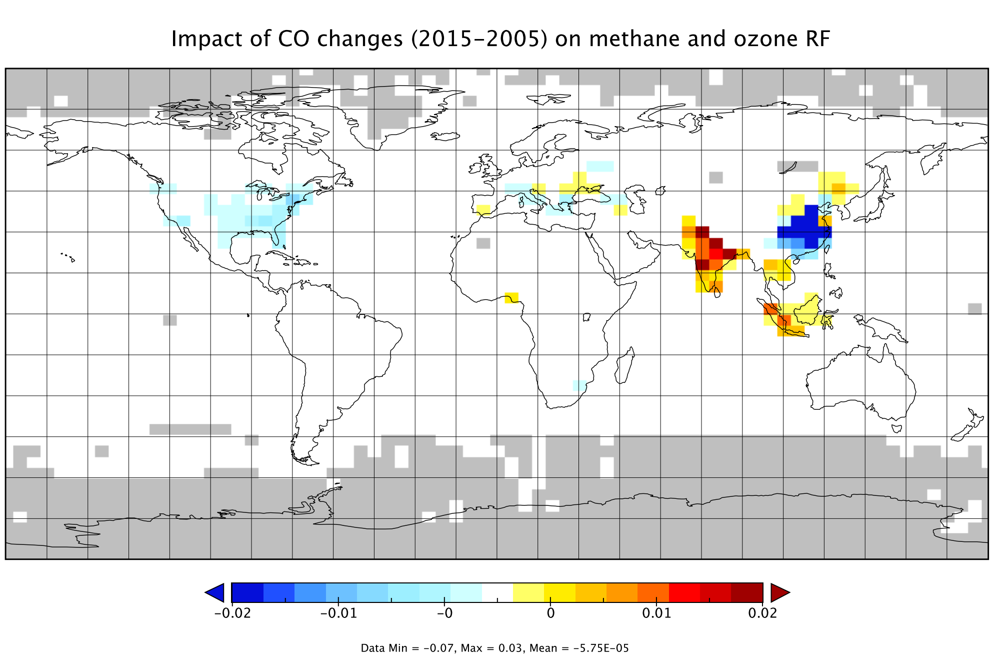


Impact of decadal CO on O3 and CH4 Radiative Forcing

Changes in decadal RF from CO has strongly opposing effects between decreases in Eastern China (max: -0.07 mW/m²) and increases in Northeastern India (max: 0.03 mW/m²)

Southeast Asia show modest increases. An outcome of South-south trade (Meng et al, Nature Comm. 2018)?

Effect of biomass burning in during El Niño in Indonesia.

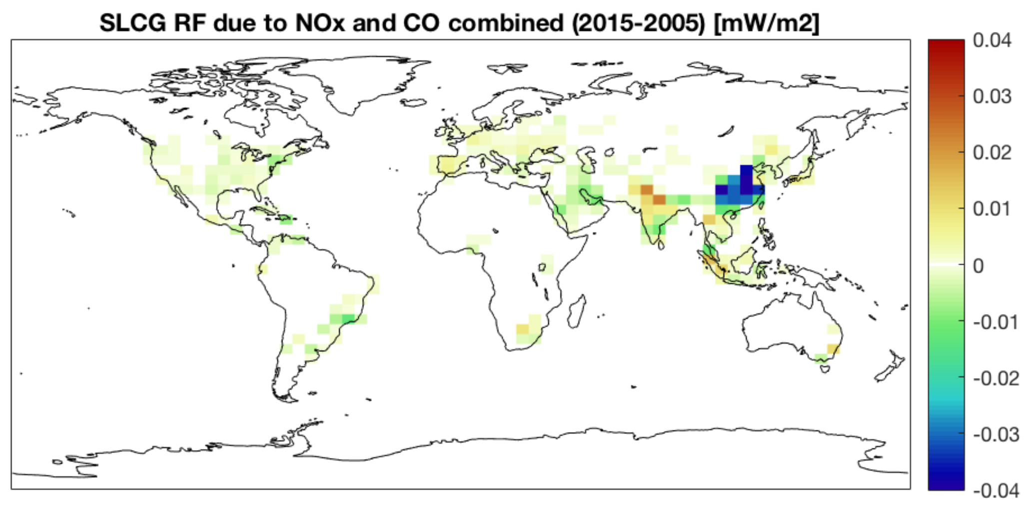


A Battle of the Tiger and the Dragon

Decreases in CO and increases in NOx emissions in China have dominated decadal radiative forcing from SLCPs: -0.44 mW/m^2

India, however, had compensating effects from increases in NOx and CO emissions, leading to a small net change: -0.05 mW/m^2

O3 RF efficiency to NOx in India is substantially higher than China



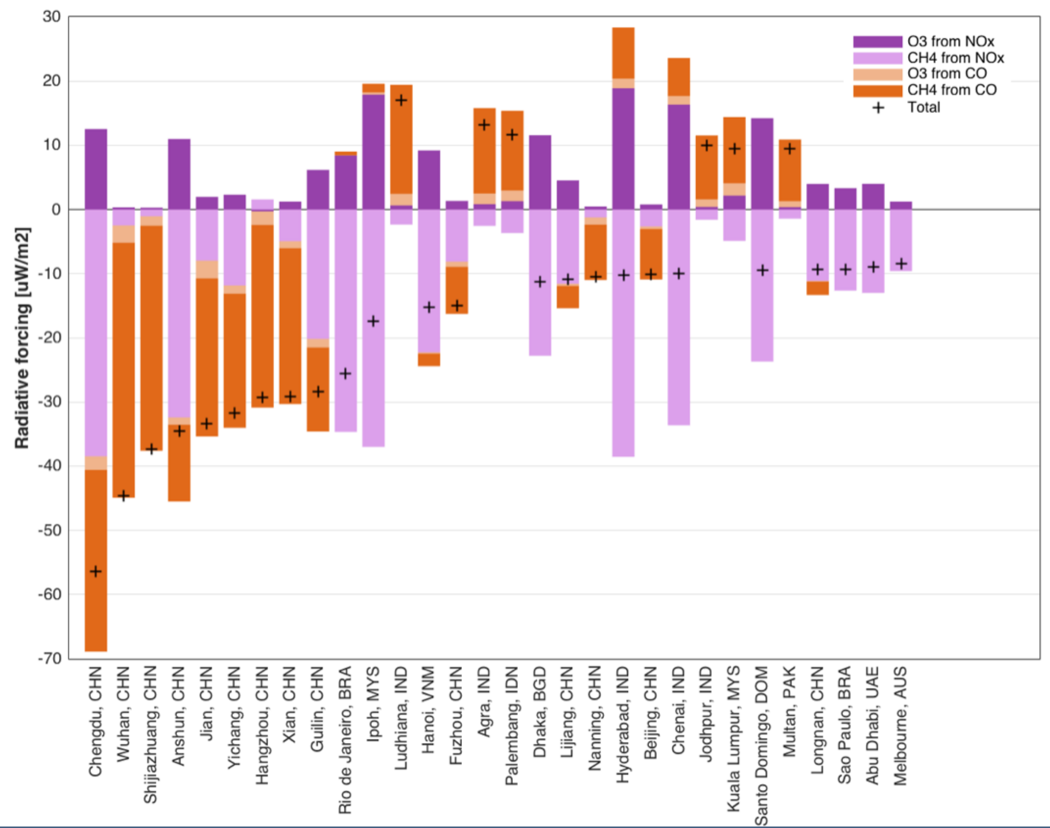
		ch4/nox	ch4/co	o3/nox	o3/co	total
2010	india	−0.12	0.02	0.06	0.00	−0.04
2010	china	−0.18	−0.30	0.05	−0.02	−0.45
2015	india	−0.29	0.17	0.15	0.03	0.05
2015	china	−0.17	−0.30	0.06	−0.02	−0.44

Urban drivers of decadal RF

The top 9 drivers of decadal RF are In China. The top 3 drivers of positive RF are in India.

The top 30 regions represent 56% of the RF contributed by places with negative RF (-0.78 mW/m²) and 39% of the RF contributed by places with positive RF (0.33 mW/m²).

Some regions have greater impact on the chemical CH4 RF than direct emissions.



Conclusions

- The past decade has witnessed dramatic changes in the landscape of air quality emissions that have impacted the planetary radiative balance.
- Using TES, MOPITT, and OMI data with adjoint modeling, we show that China has played a dominant role in reducing decadal net RF from CO and NOx through opposing emission trends
- However, India has played a substantial role in driving positive net RF primarily through increases in CO emissions.
- In conjunction with top-down CO_2 and CH_4 emissions from the NASA Carbon Monitoring System (e.g., Bowman et al, 2017, Maasakkers et al, 2019) provides a framework for urban-scale GHG accounting that will improve with time.
- This framework could support Stocktake policy deliberations

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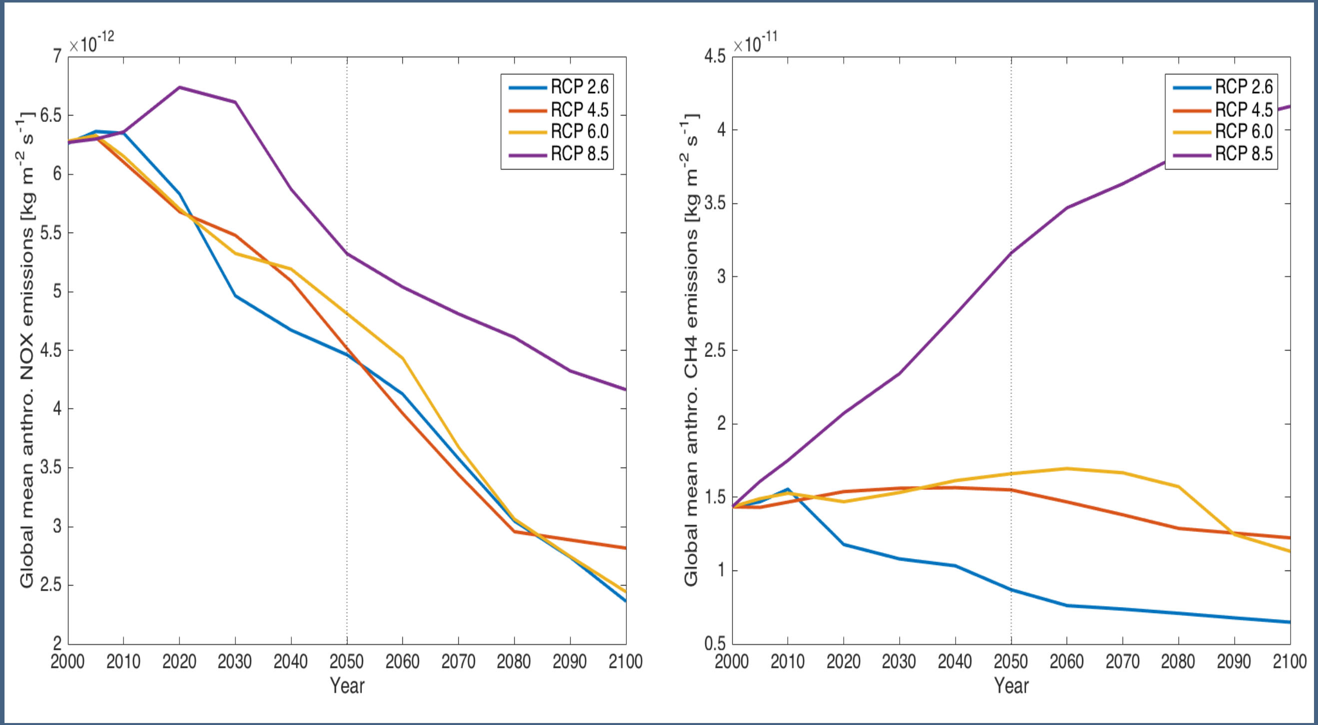
Representative Concentration Pathways



RCP 6.0 includes monotonic NOx reductions and but non-monotonic CH4 increase

Radiative Forcing in 2050 (RCP6)

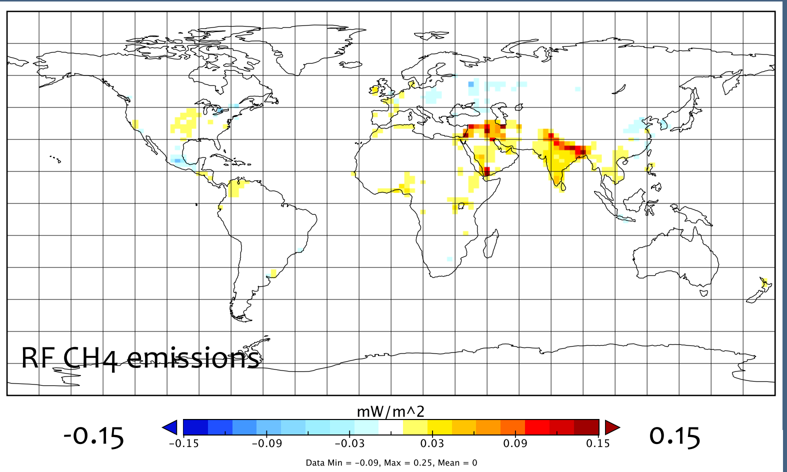
CH4 emissions RF is driven
primarily in the Middle East
And in Northern India (Gangetic plain)

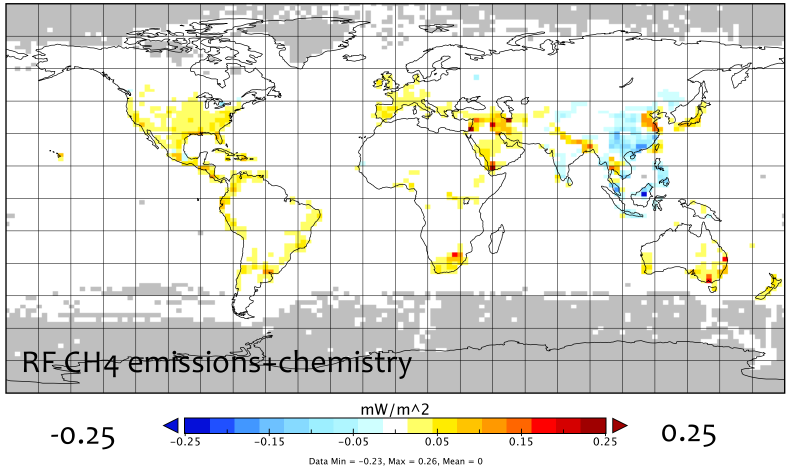
Total CH4 RF is balanced between chemical reductions in central/south China and increases in US/Europe.

Chemical-driven increases are a consequence of improved air quality standards

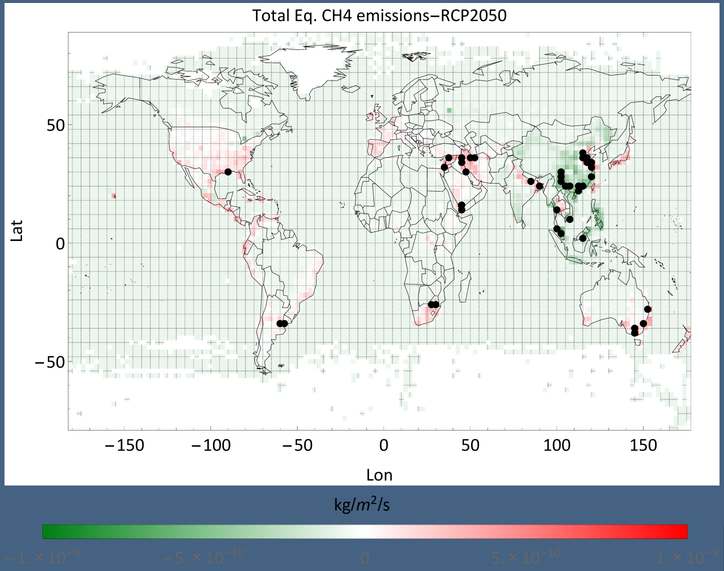
Chemical-driven decreases are a consequence of deteriorating air quality.

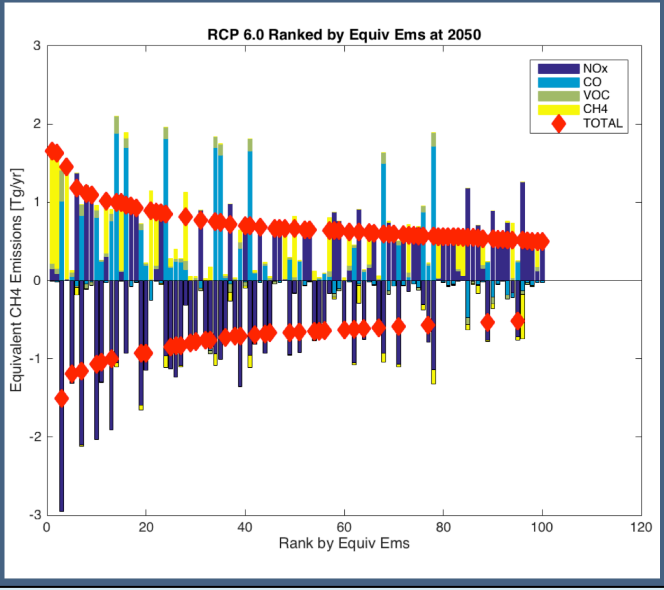
Air quality-climate *dis*benefits





Ranking total CH4 RF





RF CH4 from NOx, CO, and VOC can be converted to an equivalent emission for RF CH4.

Top 100 equivalent emissions accounts for ~30% of total global impact.

Largest impacts are in

- Middle East
  - Methane emissions
- Southeast Asia
  - NOx emissions
  - efficient OH loss
- China
  - High CO emissions
  - High NOx emissions

U.S. Climate Alliance issues short-lived climate pollutant challenge

The Alliance is calling on all national and sub-national actors to reduce short-lived climate pollutant emissions

by CCAC secretariat - 1 June, 2018

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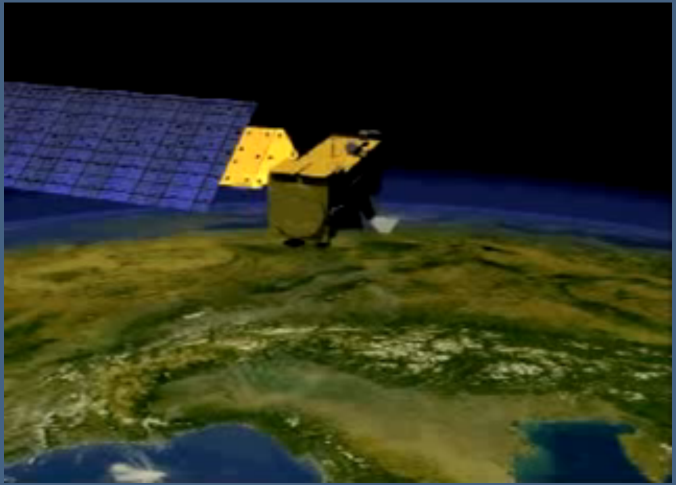
Tropospheric Emission Spectrometer



TES, launched aboard the Aura spacecraft in 2004, is a Fourier Transform Spectrometer measures infrared spectral radiances from 3.2 to 15.4 microns.

Spectral Resolution (unapodized)	0.06 cm^{-1} (nadir) 0.015 cm^{-1} (hi-res)
Spectral Coverage	650 to 3050 cm^{-1} (3.2 to 15.4 μιχρονσ)
Global survey coverage	72 observations/orbit 16 orbits/day
Spatial Resolution	0.5 x 5 km (nadir) 2.3 x 23 km (limb)
Nadir NEDT @290K (Noise Equivalent Delta Temperature)	2B1: 1.08 K 1B2: 0.36 K 2A1: 0.36 K 1A1: 2.07 K